Superconducting RF Linac Technology for Berkeley Fs X-Ray Source

(December 7, 2001)

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Introduction

- Requirement:

  600 MeV Linac plus energy recovery
  100 MeV pre-accelerator
  6.5 MV defecting RF voltage for 1 ps bunch at 3.9 GHz

- Approaches:

  Using state of the art of RF linear accelerator technology to provide high gradient RF linac and multicell crab cavities with high efficiency.

State of the Art of RF LINAC Technology

- Superconducting RF (TESLA, CEBAF, Cornell, …)
- **TESLA SC Linac:**
  - 9 cell cavity at 1.3 GHz.
  - 23.4 MV/m accelerating.
  - $R/Q \sim 1036\ \Omega$
  - Quality factor $Q_0 > 1\times10^{10}$
  - 1.4 ms pulse length with 5 Hz repetition rate.
  - Cavity with HOM damping ports.

- Normal conducting RF (SLAC, ALS, …)
- **SLAC NC Linac (x/s bands):**
  - 11.4 GHz/2.856 GHz
  - 55 MV/m (unloaded 70 MV/m) & 21 MV/m with phase advance of $150^o/120^o$, respectively.
  - $R \sim 82\ M\Omega/m$ & $50\ M\Omega/m$
  - $Q_0 \sim 4000/15000$
  - Pulse length 3.2/3.5 μs with 120 Hz rep. rate $\rightarrow$ 0.04 % DF
  - 75/65 MW klystron + sled
  - HOM damped cavity for the x band linac, tight tolerance.

600 MeV Linac Using SC and NC RF Technology

Parameters	NC S-Band Linac †	SC L-Band Linac ‡
Frequency [GHz]	2.856	1.3
Phase Advance/cell	120^0 (TW)	180^0 (SW)
Shunt Impedance [MΩ/m]	50	10^7 (1036 Ω/cavity)
Gradient [MV/m]	20	20
Pulse Length [μs]	4.5	CW
Quality Factor	15,000	10^{10}
Linac Length [m]	30	48 (~ 33 active)
Repetition Rate [Hz]	10,000	CW
Duty Factor	0.045	CW
Peak dissipated Power* [MW/m]	**8**	**4×10^{-5} (at 2K)**
Average dissipated Power* [kW/m]	**360**	**4×10^{-2} (at 2K)**
Total Input RF Power* [MW]	**10.8**	**0.256§**

† Design is based on SLAC S-Band Linac parameters [NLC Report,2001]
‡ Design is based on TESLA TTF SC linac modules [TESLA TDR,2001]
* Without considering beam power
§ Calculated by Dr. J. Delayen during our recent visit at JLAB [Nov. 2001]

Superconducting RF Linac Technology

Superconducting RF linac technology is clearly a winning choice with the following considerations:

- Less input RF power
- Wakefield: $W_L \sim f^2$, $W_T \sim f^3$
- Technology available (TESLA, JLAB, Cornell,etc..)
- Small footprint

Current study and design are based on TESLA TTF cryomodules

Recent visit at JLAB, we found that CEBAF energy upgrade cavity aiming at 20 MV/m gradient at 1.5 GHz with a 7-cell cavity, which is attractive if it becomes available. Collaboration with JLAB energy upgrade programs is important and helpful to the fs x-ray source design study, and in building up our SC technology capability at LBNL.

Superconducting RF - TESLA Cryomodules

- We base our linac design on TESLA TTF SCRF cryomodules.
- CEBAF energy upgrade cryomodule is also attractive.

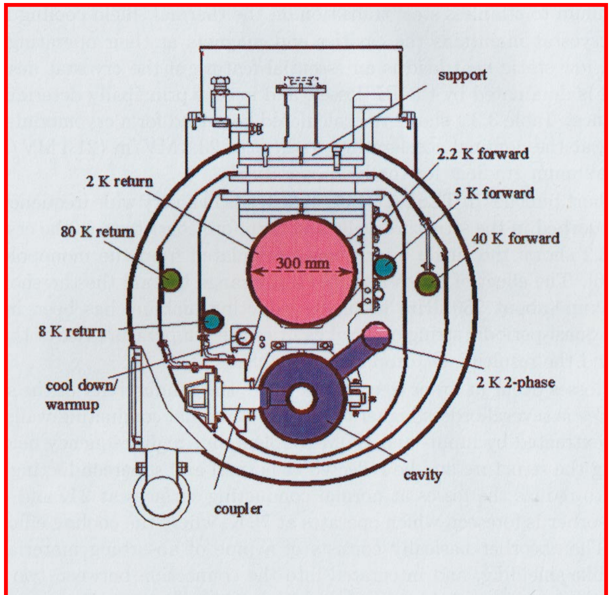
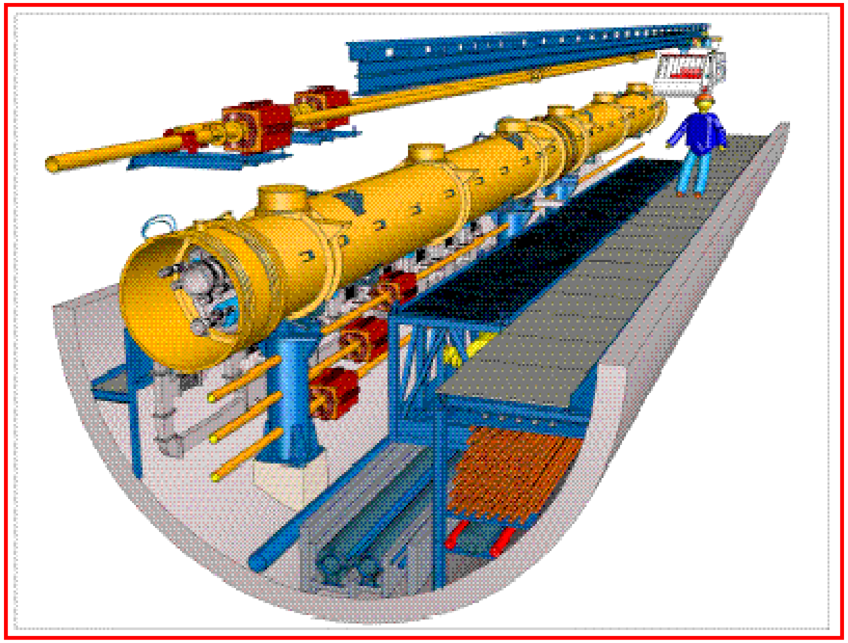


Figure 3.3.2: *Cross section of cryomodule.*

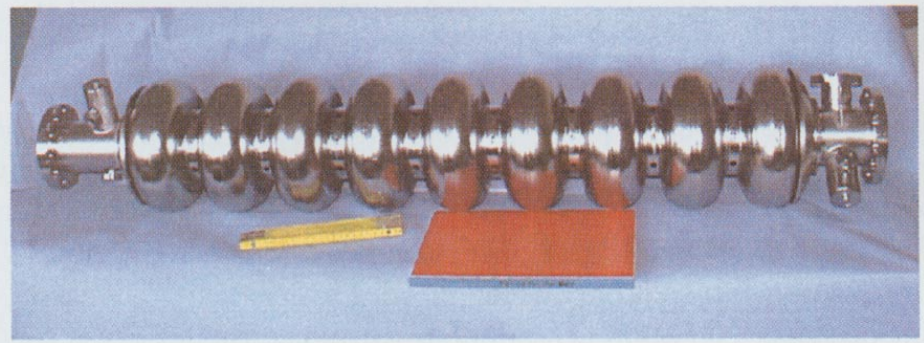


TESLA superconducting RF Cryomodules

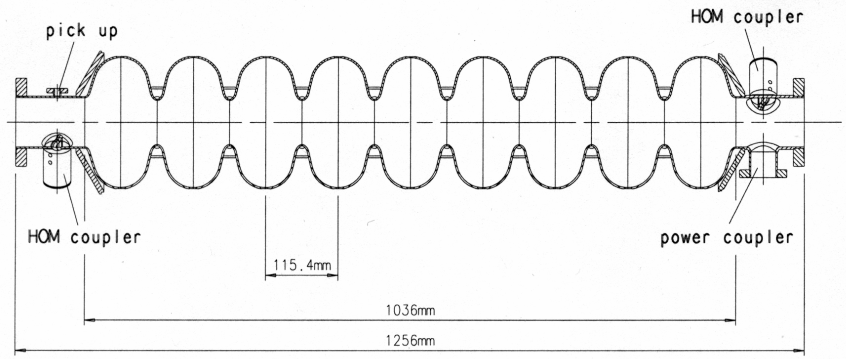
The TESLA Superconducting RF Cavity

The 600 MeV Linac parameters with comparison with the TESLA Linac

Parameters	TESLA	Fs Linac
E_{acc} [MV/m]	23.4	20
Frequency [GHz]	1.3	1.3
Quality factor	1×10^{10}	1×10^{10}
Cavity length [m]	1.038	1.038
ZT^2/Q [Ω]/cavity	1036	1036
Module length [m]	12	12
Cavities/module	8	8
Operation mode	Pulsed	CW
Pulse length[ms]	1.37	CW
Repetition rate [Hz]	5	CW
Duty factor [%]	0.685	100
Power loss/cavity[W]	0.4	42
Beam current [mA]	9.5	0.04
Bandwidth [Hz]	520	65
Q_{ext}	2.5×10^6	2×10^7
RF power/ module	1.85 MW	66 kW
Dynamic load at 2K (for 4 modules) [kW]	0.0125	1.3



The photo of 9-cell niobium cavity for TESLA



9-cell SC cavity for TESLA with E_{acc} = 23.4 MV/m

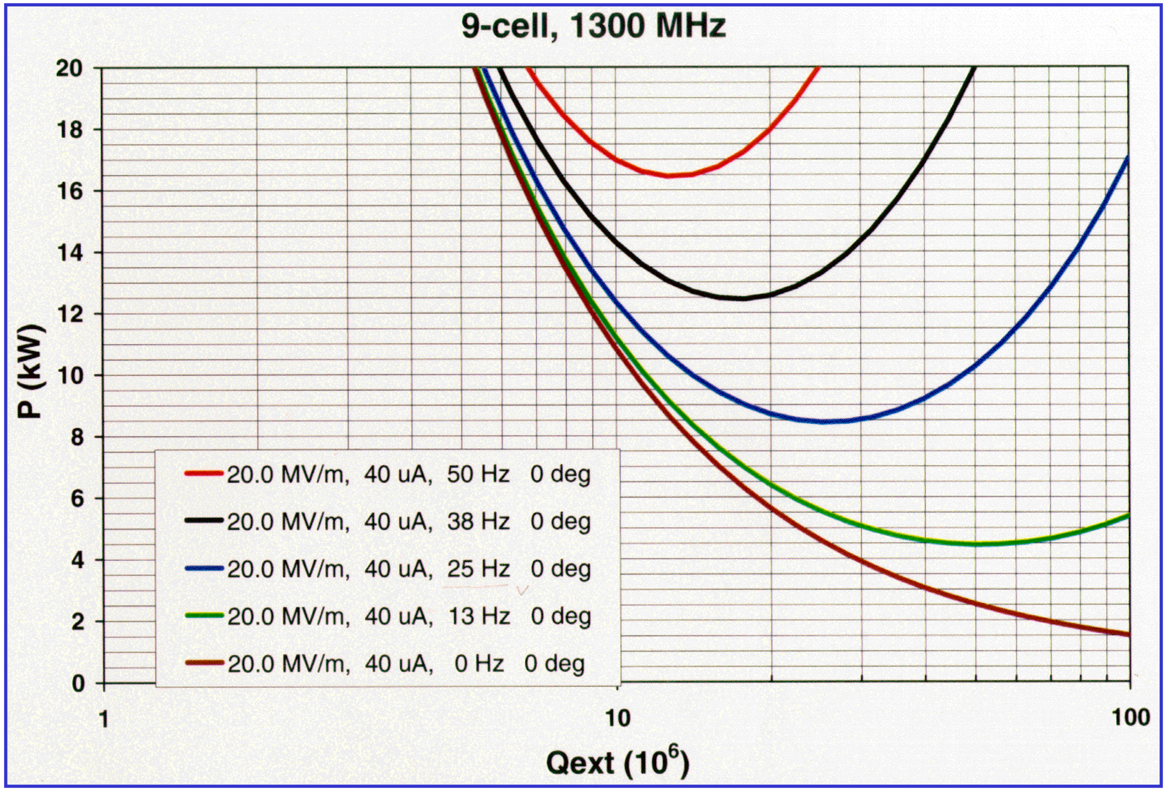
RF Coupling, Bandwidth and Frequency Stability

$$P_G = \frac{1}{4\beta_c}(1+\beta_c+b)^2 P_W ; \beta_c = \frac{Q_0}{Q_{ext}} ; b = \frac{P_{beam}}{P_W}$$

Where:
- P_G ~ RF power from klystron
- P_W ~ RF power dissipation on cavity wall
- P_{beam} Beam power
- β_c ~ RF coupling constant
- Q_0 ~ Quality factor of the cavity
- Q_{ext} ~ External quality factor
- b ~ Ratio of beam power to power dissipation on cavity wall

With 25 Hz detuning, Q_{ext} of $2\times10^7 \rightarrow$ 65 Hz bandwidth, we need 8 kW/cavity at β_c= 500 *

* Calculated by Dr. J. Delayen at JLAB



RF Coupler, Bandwidth and Frequency Stability

- RF coupling is typically determined by beam loading and power dissipation on cavity wall, but for SC cavity it is also determined by the stability of cavity frequency to microphonics and Lorentz forces.
- Input RF power depends on the cavity bandwidth.
- RF coupler developed for TESLA linac can be directly used. TESLA coupler is capable of handling 12 kW average per cavity.
- Each cavity has to be individually powered by its own klystron for better control of the amplitude and phase stability (identical RF system for each cavity) to control beam energy spread.

- CEBAF energy upgrade plans to operate with higher external Q by improved controlling of microphonics using feedback systems. Collaborating with their research in this area is important to gain valuable experience.

RF Coupler, Bandwidth and Frequency Stability

CEBAF upgrade, 1.497 GHz, 7-cell cavity, 12.5 MV/m, $Q_0 = 6.5 \times 10^9$

MICROPHONICS TESTING OF THE CEBAF UPGRADE 7-CELL CAVITY
G. Davis, J. Delayen, M. Drury, T. Hiatt, C. Hovater, T. Powers, J. Preble,
TJNAF, Newport News, VA 23606, USA
PAC2001, Chicago, 2001

Measure FM of the cavity at 1.5 GHz resonant mode due to microphonics:

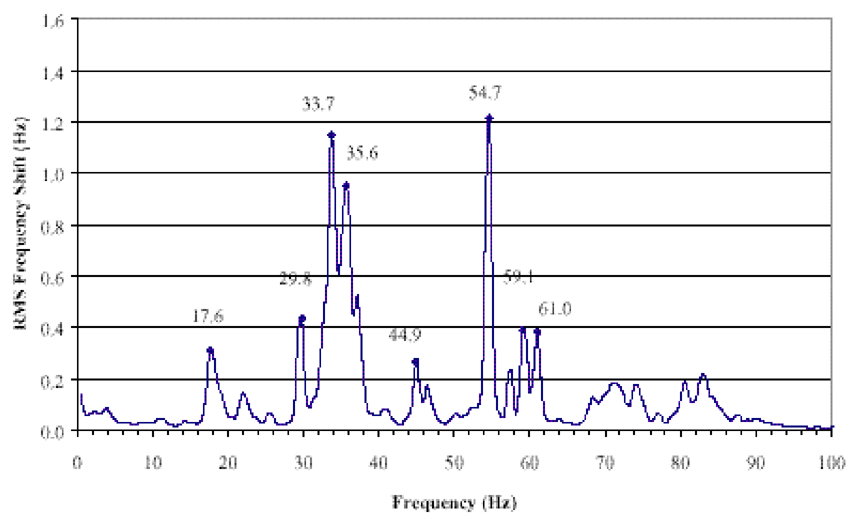


Figure 2: Cryomodule Response, Background Vibration.

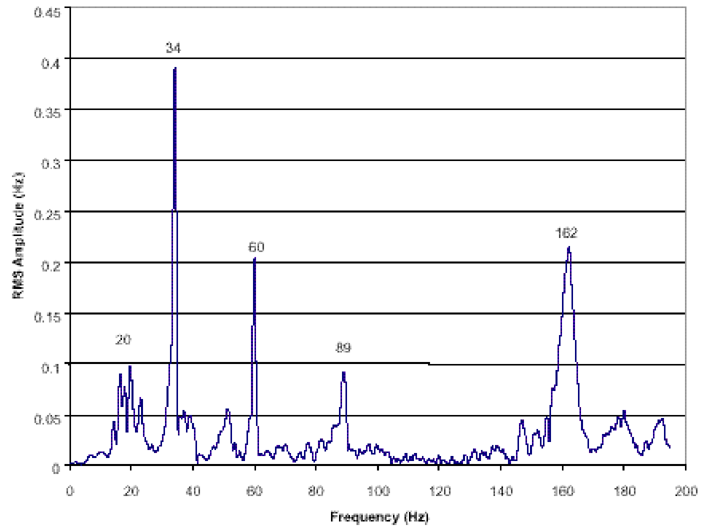


Figure 6: Cryomodule Impulse Response.

Integrate over spectrum to obtain rms frequency fluctuations of 2.5 Hz

1.3 GHz SCRF requirements and Cryosystem

Five cryomodules (including an injector module) at CW operation with gradient of 20 MV/m for main linac and 15 MV/m for the injector

Klystron power required:
300 kW RF power $\rightarrow$ 500 kW wall-plug power (60%efficiency)
860 kW wall-plug power (CEBAF klystron 35% efficiency)

$$\boxed{R_{BCS} \propto 2\times 10^{-4}\,\frac{1}{T}\left(\frac{f}{1.5}\right)^2 e^{-1.76\frac{T_c}{T}}}$$

BCS Loss increases by a factor of 50 at 4 K compared with at 2 K. Power dissipation of 2 kW at 2 K is higher than TESLA, but looks Okay based on the experience from CEBAF.

1.3 GHz SCRF requirements and Cryosystem (cont'd)

Five cryomodules (including an injector module) at CW operation at at gradient of 20 MV/m for main linac, 15 MV/m for the injector:

1.52 kW power dissipation at T = 2 K

$$P_{Compressor} = P_{2K}\,\frac{300-T}{T\eta}$$

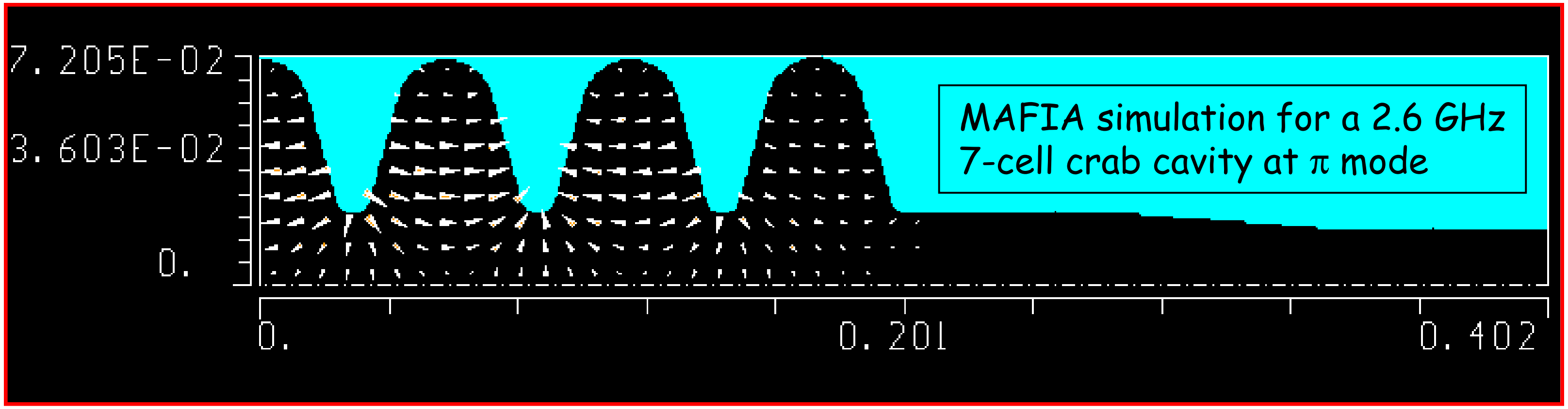
Specify 50% above expected load,

2.2 MW wall-plug power (η= 16%) is needed for cryosystem $\rightarrow$ Okay !

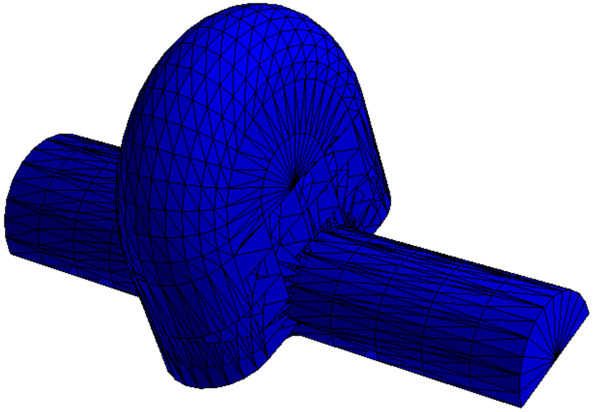
Multicell Crab Cavity

- 6.5 MV RF deflecting voltage at 3.9 GHz for a 1 ps bunch.
- At crabbing mode, due to the beam iris, the cavity is a hybrid of TM and TE modes. On the beam axis , both transverse electric and magnetic fields act on the beam.
- We base the crab cavity design on KEK-B crab cavity, Cornell and Fermilab SC multi-cell deflecting RF cavities for Kaon separation.

Eight 9-cell crab cavities with (R/Q) = 495 Ω, $Q_0 = 2\times10^9$
at 20 - 25 MV/m peak surface fields → 5 MV/m deflecting voltage

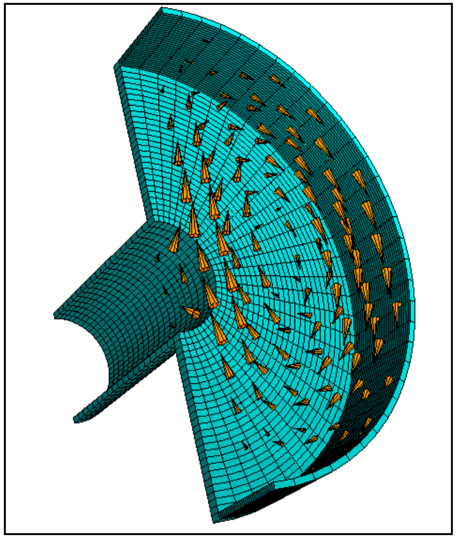


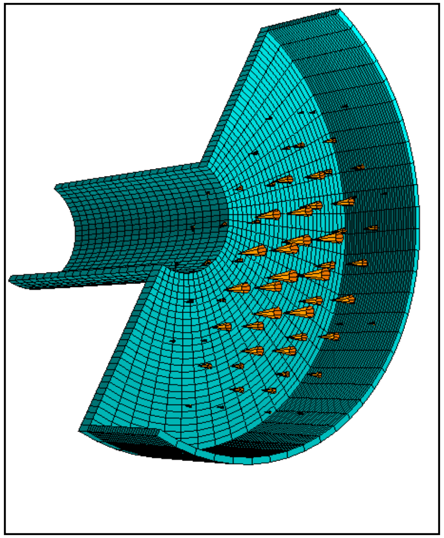
Multicell Crab Cavity (Continued)



Power dissipation 27 W/cavity at 2 K
$\rightarrow$ 1.8 kW RF power/cavity at Q_{ext} 6.5×10^9
giving 60 Hz bandwidth
For eight cavities:
0.3 MW wall-plug power for the cryosystem
24 kW wall-plug power for the RF at 3.9 GHz
[41 kW,CEBAF]

$$\frac{R}{Q} = \frac{|\int E_z(r=r_0)e^{jkz}dz|^2}{(kr_0)^2\omega U}$$





- To separate two degenerated dipole modes in a cylindrical cavity for the required polarization, the cavity needs to be perturbed or squashed in one plane.
- Lower order monopole mode may need to be damped.
- The multi-cell cavity is a backward wave structure.
- Collaboration with KEK, Cornell, JLAB

Summary of the RF and Cryosystem

RF Power:

Name	Frequency	Power
Linac	1.3 GHz	260kW
Injector	1.3 GHz	40 kW
RF Gun	1.3 GHz	275 kW
Beam Power		25 kW
Subtotal		600 kW
Crab Cavity	3.9 GHz	16 kW

Total wall Power 1.03MW

(60% efficiency)

Cryosystem:

At T = 2 K:

Five cryomodules	1.52 kW
Eight crab cavities	220 W
Subtotal	1.74 kW

Total Wall Power 2.5 MW

(at η = 16 %)

Future Plans

- Collaboration with JLAB on their energy upgrades to gain experience on
  - low level RF control: phase and amplitude stability $\rightarrow$ beam energy spread
  - high external Q operation: bandwidth and RF power
  - frequency stability control: phase+amplitude
  - SC RF operation
  - cryomodule engineering (choice of TESLA/CEBAF cryomodules)
- Synchronization study of the crab cavity
- Crab cavity R & D may need 2 -3 years (collaborations)
- Visit TESLA facility, ACCEL to further investigate TESLA cryomodules
- Site specific study of magnetic shielding which is important in improving Q_0
- Investigate cryogenics requirements and operations